

# **Aquarius CAP Algorithm and Data User Guide**

*Version: 5.0*

*Wenqing Tang, Simon Yueh, Alexander Fore, and Akiko Hayashi*

*Jet Propulsion Laboratory*

*California Institute of Technology*

*Date: September 20, 2018*

### *Contributors*

The Aquarius geophysical model functions for the CAP algorithm were developed by Dr. Wenqing Tang; the operational setup and processing of the CAP algorithm was completed by Dr. Alex Fore; the setup of data portal and data transfer was performed by Mrs. Akiko Hayashi.

## Document Change Log

Date		Version	Changes/Comments
February 20, 2013	Page 8	2.0	Updated the cost function by adding two additional terms to constrain the wind speed and direction retrieval
February 20, 2013	Page 11	2.0	Add 10 to the flag to indicate possible rain contamination
February 20, 2013	Pages 5 and 6	2.0	Include the significant wave height as a modeling parameter for radar backscatter and excess emissivity
June 20, 2014	All	3.0	Include the rain corrections to GMFs of radar backscatter and excess emissivity and provide references to the articles on product validation results.
Sept. 20, 2015	Page 6, 8-11, 13-27	4.0	Include the rain corrections to GMFs of excess emissivity with rain-induced near surface stratification accounted for by the Rain Impact Model; and provide results of validation in comparison with APDRC Argo-gridded product and in situ data from moored buoys.

Sept. 26, 2018		5.0	<ol style="list-style-type: none"> <li>1. The Geophysical Model Functions (GMFs) are updated to 4<sup>th</sup> order harmonics and include the effect of sea surface temperature (SST) and stability at air-sea interface.</li> <li>2. The source of the ancillary sea surface temperature (SST) has been changed from NOAA OI SST to the SST from the Canadian Meteorological Center (CMC).</li> </ol>
----------------	--	-----	---

## Contents

I. Purpose .....	5
II. Introduction .....	6
III. Geophysical Model Function .....	6
IV. Overview of CAP algorithm .....	8
V. CAP L2 Data and Format .....	9
A. File name convention .....	9
B. Description of datasets in HDF .....	9
1. CAP outputs .....	9
2. Carryover from Aquarius L2 files .....	11
VI. CAP L3 Data and Format .....	11
VII. References .....	12

## I. PURPOSE

This document provides an overview of the Combined Active-Passive (CAP) Algorithm for the sea surface roughness correction to enable the retrieval of sea surface salinity, wind speed and direction from Aquarius data. The results from the CAP algorithm are output to files in HDF5 format. This document describes the datasets in the files and their format.

## II. INTRODUCTION

The measurement principle for salinity remote sensing is based on the response of the L-band (1.413 GHz) sea surface brightness temperatures ( $T_B$ ) to sea surface salinity [1]. The influence of wind speed on L-band  $T_B$  has been shown to be about 0.2 to 0.3 K for one  $\text{m.s}^{-1}$  change in wind speed by many field studies [2-7]. To achieve the required 0.2 practical salinity unit (psu) accuracy for Aquarius mission, the impact of sea surface roughness (e.g. wind-generated ripples, foam, and swells) on the observed brightness temperature has to be accurately corrected, ideally to better than one tenth of a degree Kelvin.

The Aquarius radiometer and scatterometer have been fully operating from August 25, 2011 to June 7, 2015. Other than the interruptions caused by a few spacecraft maneuvers, the data acquisition has been continuous. The Aquarius instrument has three antenna beams, operating at about 29, 38 and 46 degrees [8]. Each antenna beam has one radiometer (1.413 GHz), which can acquire the first three Stokes parameters of microwave radiation. The antenna feeds are shared with the scatterometer (1.26 GHz), which acquire the normalized radar cross sections ( $\sigma_0$ ) for co- and cross-polarizations, including VV, HH, VH and HV polarizations.

The Aquarius radiometers make partial polarimetric measurements for the first three Stokes parameters, I, Q, and U [9]. I and Q correspond to the sum and difference of the vertically polarized brightness temperature ( $T_{BV}$ ) and horizontally polarized brightness temperature ( $T_{BH}$ ).  $T_{BV}$  and  $T_{BH}$  are measures of the power of the vertically polarized electrical field ( $E_V$ ) and horizontally polarized electric field ( $E_H$ ), while the third and fourth Stokes parameters (U and V) signify the correlation between  $E_V$  and  $E_H$ :

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} T_{BV} + T_{BH} \\ T_{BV} - T_{BH} \\ U \\ V \end{bmatrix} \propto \begin{bmatrix} \langle |E_V|^2 \rangle + \langle |E_H|^2 \rangle \\ \langle |E_V|^2 \rangle - \langle |E_H|^2 \rangle \\ 2 \text{Re} \langle E_V E_H^* \rangle \\ 2 \text{Im} \langle E_V E_H^* \rangle \end{bmatrix} \quad (1)$$

The angular brackets denote the ensemble average of the enclosed quantities. Aquarius does not measure the fourth Stokes V.

## III. GEOPHYSICAL MODEL FUNCTION

The matchup data using either SSM/I or NCEP wind for binning have been used to develop the geophysical model functions (GMF) for Aquarius [13], which relate the microwave backscatter or excess surface emissivity to the wind speed ( $w$ ) and direction ( $\phi$ ). In addition, we include the NOAA WaveWatch-III Significant Wave Height (SWH), CMORPH rain rate (R), sea surface temperature (SST) from the Canadian Meteorological Center, and air temperature ( $T_a$ ) from NCEP to develop the GMF and as ancillary for retrieval.

The radar GMF is expressed as:

$$\sigma_{0,p} = \sigma_p^{wind} + \sigma_p^{rain} + \sigma_p^{SST} + \sigma_p^{dT} \quad (2)$$

where p stands for VV (V-transmit/V-receive) and HH (H-transmit/H-receive), respectively. The wind/wave induced roughness is modeled in terms of 4<sup>th</sup> order cosine series:

$$\sigma_p^{wind} = A_{0,p}^{wind}(w, swh)[1 + \sum_{n=1}^4 A_{n,p}^{wind}(w) \cos(n\phi)] \quad (3)$$

The residuals after applying the wind/wave correction (i.e.  $\sigma_p^{meas} - \sigma_p^{wind}$ ) are analyzed to model subsequently the effects of rain (Eq. 4), SST (Eq. 5) and the surface stability parameterized in terms of the temperature difference at the interface of air and seawater (i.e.  $dT = T_a - SST$ ) in Eq. 6.

$$\sigma_p^{rain} = A_{0,p}^{rain}(w, R) + \sum_{n=1}^4 A_{n,p}^{rain}(w, R) \cos(n\phi) \quad (4)$$

$$\sigma_p^{SST} = A_{0,p}^{SST}(w, SST) + \sum_{n=1}^4 A_{n,p}^{SST}(w, SST) \cos(n\phi) \quad (5)$$

$$\sigma_p^{dT} = A_{0,p}^{dT}(w, dT) + \sum_{n=1}^4 A_{n,p}^{dT}(w, dT) \cos(n\phi) \quad (6)$$

The radiometer model function for excessive emissivity is expressed as:

$$\Delta e_p = e_p^{wind} + e_p^{rain} + e_p^{SST} + e_p^{dT} \quad (7)$$

where p stands for V-pol and H-pol. The largest term is from wind/wave induced roughness,

$$e_p^{wind} = e_{0,p}^{wind}(w, swh) + \sum_{n=1}^4 e_{n,p}^{wind}(w) \cos(n\phi) \quad (8)$$

The residuals after applying the wind/wave correction are analyzed to model subsequently the effects of rain (Eq. 9), SST (Eq. 10) and the surface stability (Eq. 11).

$$e_p^{rain} = e_{0,p}^{rain}(w, R) + \sum_{n=1}^4 e_{n,p}^{rain}(w, R) \cos(n\phi) \quad (9)$$

$$e_p^{SST} = e_{0,p}^{SST}(w, SST) + \sum_{n=1}^4 e_{n,p}^{SST}(w, SST) \cos(n\phi) \quad (10)$$

$$e_p^{dT} = e_{0,p}^{dT}(w, dT) + \sum_{n=1}^4 e_{n,p}^{dT}(w, dT) \cos(n\phi) \quad (11)$$

The third Stokes parameter for the L-band frequency is modeled by the sine function of the wind direction.

Given the GMF for excess surface emissivity, following are the complete descriptions of the radiometer model function, which relates the brightness temperatures to surface salinity (SSS), SST, wind speed and direction, SWH, R, and dT:

$$TB_V(SSS, SST, w, \phi, swh, R, dT) = TB_V^{flat}(SSS, SST) + SST \cdot \Delta e_V(w, \phi, R, SST, dT) \quad (12)$$

$$TB_H(SSS, SST, w, \phi, swh, R, dT) = TB_H^{flat}(SSS, SST) + SST \cdot \Delta e_H(w, \phi, R, SST, dT) \quad (13)$$



$$U(SSS, SST, w, \phi) = U_1(w) \sin \phi + U_2(w) \sin 2\phi \quad (14)$$

$T_{Bflat}$  is the brightness temperature for flat water surfaces computed using the water dielectric constant model [10, 11, 16, 20] for given Reynolds SST and SSS. The subscript “p” stands for the polarization. The impact of ocean waves on L-band brightness temperatures and backscatter from the ocean surface was analyzed in [23].

#### IV. OVERVIEW OF CAP ALGORITHM

The CAP algorithm retrieves the salinity and wind simultaneously by finding the best-fit solution to minimize the difference between the Aquarius data and the model functions described in Eqs. (2)-(9). The earlier versions of the CAP algorithm [12, 13] use different functional forms for the cost function. After gaining more knowledge about the characteristics of the Aquarius L-band microwave data, particularly the weak response of radar backscatter to wind speed near the crosswind direction, we included the last two additional terms in Eq. (10) to constrain the wind speed and direction solutions primarily for near the crosswind directions. Detailed description of the CAP V3.0 retrieval algorithm is provided in [20]. The major updates to V2.0 include improved correction of reflected galactic radiation, geophysical model functions and cost function. The cost function for the CAP Version 3 and 4 algorithm is

$$F_{cap}(SSS, w, \phi) = \sum_{p=V, H} \frac{(T_{Bp} - T_{Bpm})^2}{\Delta T^2} + \sum_{p=V, H} \frac{(\sigma_{0p} - \sigma_{0pm})^2}{(\gamma_p \sigma_{0p})^2} + \frac{(w - w_{NCEP})^2}{\Delta w^2} + \frac{\sin^2[(\phi - \phi_{NCEP})/2]}{\delta^2} \quad (15)$$

The weighting factors for the Aquarius data are set according to the expected measurement and modeling uncertainties. We let  $\Delta T$  be the Noise-Equivalent-Delta-T (NEDT) of radiometer and  $\gamma_p$  be 1.4 times of the radar measurement sensitivity ( $k_{pc}$ ). The values of NEDT and  $k_{pc}$ , a function of signal-to-noise ratio, have been pre-computed and saved in the Aquarius L2 data files. The value of  $\Delta w$  is  $1.5 \text{ ms}^{-1}$ , a rather weak constraint because the accuracy of CAP wind speeds is estimated to be about  $0.7 \text{ ms}^{-1}$  [13]. The value of  $\delta$  is 0.2, which will constrain the wind direction to be within an RMS deviation of 11 degrees from the NCEP wind direction. Our previous analysis [13] indicates that the directional accuracy of the CAP algorithm is about 10 degrees or better for wind speeds of  $15 \text{ ms}^{-1}$  or above. The effect of the last term will not impact the accuracy of the CAP wind direction retrieval for high winds, but will help constrain the wind direction solution for low winds, for which the L-band data have a weak response to wind direction.

For the Aquarius data, we applied the conjugate gradient technique using a modified Levenberg-Marquardt algorithm [14] to find the local minima of  $F_{cap+}$ . There are in general four local minima (ambiguous solutions). This is due to the expansion of the model function for wind direction by including up to the second harmonics of the cosine series. For each given wind speed solution, there will in general be four direction solutions, except when the relative wind direction is along upwind, or downwind or crosswind. This can be easily understood by considering the special case when the  $A_1$  coefficients are zero in the model functions. If the first

harmonic coefficient  $A_1$  is zero, these four solutions, corresponding to the inversion of  $\cos 2\phi$ , are  $\phi$ ,  $-\phi$ ,  $\phi+180^\circ$  and  $180^\circ-\phi$ . If  $A_1$  and  $e_{B1}$  are small, then the third and fourth solutions will shift slightly away from  $\pm\phi+180^\circ$ . Note that because the cosine series are even functions, the solution pair,  $\pm\phi$ , will produce identical values for model functions, and consequently lead to the same SSS and wind speed solutions. The same is true for the  $\pm\phi+180^\circ$  solution pair.

A nominal technique developed for the current or past spaceborne wind scatterometer and radiometer missions is the use of numerical weather analysis, such as NCEP or European Center for Medium Range Forecasts (ECMWF), or special wind features to assist the selection of solutions [15]. For salinity and wind speed retrievals, the discrimination of ambiguities is a less challenging issue than ocean wind scatterometers or radiometers because what is needed is to separate the four solutions into two pairs,  $\pm\phi$  and  $\pm\phi+180^\circ$ , which are separated by about 180 degrees. As previously discussed, each pair will have the same SSS and wind speed values. In our analysis, we use the numerical wind analyses to select the solution by selecting the solution with the closest wind direction to NCEP.

## V. CAP L2 DATA AND FORMAT

The Aquarius CAP L2 files contain the CAP algorithm outputs and a few datasets in the Aquarius L2 data files, in HDF format.

### A. File name convention

The file names are similar to the Aquarius L2 files. The first part of the file name is the same as that in the Aquarius L2 files. We added the extension '.cap' to it.

For example, Q2012001012500.L2\_SCI\_V5.0.cap, is the file for the data pass started at 01:25:00 UT on day 1, 2012. "L2\_SCI\_V5.0" indicates the version of Aquarius L2 files used for the CAP processing.

### B. Description of datasets in HDF

The datasets in the HDF5 files are part of the root file, not in a "Aquarius Data" group. Each dataset has 4083 blocks for 3 antenna beams.

A simple way to separate the data from ascending and descending passes for ocean observations is to use the first array index of the dataset. If the first array index is smaller (greater) than 2042, then the data are from ascending (descending) orbits.

#### 1. CAP outputs

The CAP data and critical time and location data sets are outlined below.

Dataset	Size	Format	Unit	Valid range	Description
---------	------	--------	------	-------------	-------------

	(Block, Beam)				
Sec	Dataset {4083}	double float	Seconds	0.d0 to 86399.999999d0	Block time in seconds of day
beam_clat	Dataset {4083, 3}	float	Degree	-90 to 90	Latitude of footprint
beam_clon	Dataset {4083, 3}	float	Degrees	-180 to 180	Longitude of footprint
SSS_cap	Dataset {4083, 3}	float	Psu	0 to 50	SSS from the CAP algorithm
SSS_cap_rc	Dataset {4083,3}	Float	Psu	0 to 50	SSS from the CAP with rain correction if RR>0; SSS_cap_rc is identical to SSS_cap if no rain (RR=0), or there is no rain data matchup with Aquarius
SSS_cap_v	Dataset {4083, 3}	float	Psu	0 to 50	SSS retrieved from the V-pol TB using the scat_wind_speed for excess surface emissivity correction
wind_speed_cap	Dataset {4083, 3}	float	Meters per sec	Greater than 0	Wind speed retrieved from the CAP algorithm
wind_dir_cap	Dataset {4083, 3}	float	Degrees	-180 to 180	Wind direction retrieved from the CAP algorithm
cap_flag	Dataset {4083, 3}	H5T_NA TIME_U CHAR		0 to 5, 10 to 15 and 100*	Flag for CAP retrieval
scat_wind_speed	Dataset {4083, 3}	float	Meters per sec	Greater than 0	Wind speed retrieved from the Aquarius scatterometer data using the NCEP wind direction as ancillary information

wind\_dir\_cap is the wind direction retrieved from the Aquarius data, and is the direction from with respect to the north in clockwise direction. Its error is less than 20 degrees RMS at greater than 12 m/s wind speeds for beam 1 and 10 m/s for beams 2 and 3.

cap\_flag: The flag for CAP algorithm retrieval with the values of 0, 1, and 2 for valid SSS retrieval and 3 and 4 for invalid SSS retrieval. If the matchup rain rate (RR) from SSMIS or WindSat is greater than zero, we add 10 to the flag to indicate possible rain contamination.

- 0 for  $\text{abs}(\text{wind\_speed\_cap} - \text{anc\_wind\_speed}) < 15 \text{ m/s}$
- 1 for  $\text{abs}(\text{wind\_speed\_cap} - \text{anc\_wind\_speed}) < 30 \text{ m/s}$

- 2 for  $\text{abs}(\text{wind\_speed\_cap} - \text{anc\_wind\_speed}) > 30$  m/s
- 3 for  $\text{wind\_speed\_cap} < 0$  or  $\text{sss\_cap} < 0$  or  $\text{sss\_cap} > 50$
- 4 for no retrieval
- 5 for  $\text{TBerr} \geq 0.4$  K, where  $\text{TBerr} = \sqrt{(\text{TB}_V^{\text{meas.}} - \text{TB}_V^{\text{mod.}})^2 + (\text{TB}_H^{\text{meas.}} - \text{TB}_H^{\text{mod.}})^2}$
- 10 for  $\text{abs}(\text{wind\_speed\_cap} - \text{anc\_wind\_speed}) < 15$  m/s and  $\text{RR} > 0$
- 11 for  $\text{abs}(\text{wind\_speed\_cap} - \text{anc\_wind\_speed}) < 30$  m/s and  $\text{RR} > 0$
- 12 for  $\text{abs}(\text{wind\_speed\_cap} - \text{anc\_wind\_speed}) > 30$  m/s and  $\text{RR} > 0$
- 13 for  $\text{wind\_speed\_cap} < 0$  or  $\text{sss\_cap} < 0$  or  $\text{sss\_cap} > 50$  and  $\text{RR} > 0$
- 14 for no retrieval and  $\text{RR} > 0$
- 15 for  $\text{TBerr} \geq 0.4$  K and  $\text{RR} > 0$

\*We added 100 to the `cap_flag` if  $\text{abs}(\text{rad\_TaV} - \text{rad\_TfV}) \geq 1$  or  $\text{abs}(\text{rad\_TaH} - \text{rad\_TfH}) \geq 1$ .

## 2. Carryover from Aquarius L2 files

The following are datasets carried over from the Aquarius L2 files. They are included for ease of comparison with the CAP products.

Dataset	Size (Block, Beam)	Unit	Description
SSS	Dataset {4083, 3}	Psu	SSS in the Aquarius L2 files
anc_SSS	Dataset {4083, 3}	Psu	Ancillary (HYCOM) SSS in the Aquarius L2 files
anc_surface_temp	Dataset {4083, 3}	Kelvin	SST in the Aquarius L2 files
anc_wind_speed	Dataset {4083, 3}	Meters per sec	Ancillary (NCEP) wind speed in the Aquarius L2 files
anc_wind_dir	Dataset {4083, 3}	Degrees	Ancillary wind direction (NCEP) in the Aquarius L2 files
scat_land_frac	Dataset {4083, 3}		Scatterometer land fraction in the Aquarius L2 files (unitless between 0 and 1)
scat_ice_frac	Dataset {4083, 3}		Scatterometer ice fraction in the Aquarius L2 files (unitless between 0 and 1)
land_frac	Dataset {4083, 3}		Radiometer land fraction in the Aquarius L2 files (unitless between 0 and 1)
ice_frac	Dataset {4083, 3}		Radioemter ice fraction in the Aquarius L2 files (unitless between 0 and 1)

## VI. CAP L3 DATA AND FORMAT

The Aquarius CAP L3 data contain monthly and weekly maps on  $1^\circ \times 1^\circ$  grid for both `SSS_cap` and `SSS_cap_rc`, in netcdf format. L3 data are created using Gaussian weighting with half-power and searching distances at 75 and 111 km, respectively. The filtering criteria for transferring data

from Level 2 to Level 3 are:  $\text{land\_frac} < 0.01$ ,  $\text{ice\_frac} < 0.0005$ ,  $\text{anc\_surface\_temp} > 273$ , and  $\text{cap\_flag} < 3$  or  $10 \leq \text{cap\_flag} < 13$ , in addition to checking the radiometer flag included in Aquarius L2 files for non-nominal navigation (bit-12), and pointing anomaly (bit-16).

## VII. REFERENCES

- [1] Yueh, S. H., R. West, W. J. Wilson, F. K. Li, E. G. Njoku, and Y. Rahmat-Samii, "Error sources and feasibility for microwave remote sensing of ocean surface salinity", *IEEE Trans. Geosci. Remote Sensing*, 39, 1049-1060, 2001.
- [2] Hollinger, J. P., "Passive microwave measurements of sea surface roughness", *IEEE Trans. Geosci. Electron.*, vol. GE-9, pp. 165–169, July 1971.
- [3] Camps, A., J. Font, M. Vall-Llossera, C. Gabarro, I. Corbella, N. Duffo, F. Torres, S. Blanch, A. Aguasca, R. Villarino, L. Enrique, J.J. Miranda, J.J. Arenas, A. Juliaa, J. Etcheto, V. Caselles, A. Weill, J. Boutin, S. Contardo, R. Niclos, R. Rivas, S.C. Reising, P. Wursteisen, M. Berger, and M. Martin-Neira, "The WISE 2000 and 2001 field experiments in support of the SMOS mission: Sea surface L-band brightness temperature observations and their application to sea surface salinity retrieval," *IEEE Trans. Geoscience and Remote Sensing*, vol. 42, no. 4, pp. 804-823, April 2004.
- [4] Etcheto, J., E. P. Dinnat, J. Boutin, A. Camps, J. Miller, Stephanie, J. Wesson, J. Font, and D. Long, "Wind speed effect on L-band brightness temperature inferred from EuroSTARRS and WISE 2001 field experiments." Vol. 42, no. 10, pp. 2206-2213, October 2004.
- [5] Gabarro, C. J. Font, A. Camps, M. Vall-Llossera, and A. Julia, "A new empirical model of sea surface microwave emissivity for salinity remote sensing," *Geophysical Research Letters*, vol. 31, no. 1, pp. 5, January 2004.
- [6] Camps, A., M. Vall-Llossera, R. Villarino, N. Reul, B. Chapron, I. Corbella, N. Duffo, F. Torres, J.J. Miranda, R. Sabia, A. Monerris, R. Rodriguez, "The Emissivity of Foam-Covered Water Surface at L-Band: Theoretical Modeling and Experimental Results From the Frog 2003 Field Experiment", *IEEE Trans. Geosci. Remote Sensing*, vol. 43, issue 5, pp. 925-937, May 2005.
- [7] Yueh, S. H., S. Dinardo, A. Fore, and F. Li, "Passive and Active L-Band Microwave Observations and Modeling of Ocean Surface Winds", *IEEE Trans. Geosci. And Remote Sensing*, Vol. 48, No. 8, pp. 3087-3100, August 2010.
- [8] Le Vine, D. M., G.S.E. Lagerloef, R. Coloma, S. Yueh, and F. Pellerano, "Aquarius: An Instrument to Monitor Sea Surface Salinity from Space," *IEEE Trans. Geosci. And Remote Sensing*, Vol. 45, No. 7, 2040-2050, July 2007.
- [9] Kraus, J. D., *Radio Astronomy*, 2nd. ed., 1986, Cygnus-Quasar Books, Powell, Ohio.
- [10] Meissner T. and F. Wentz, "The Complex Dielectric Constant of Pure and Sea Water From Microwave Satellite Observations", *IEEE TGARS*, vol. 42 (9), 1836 – 1849, 2004.
- [11] Klein, L., & C. Swift, "An improved model for the dielectric constant of sea water at microwave frequencies". *IEEE Trans. on Antennas and Propagation*, 25, (1), 104 – 111, 1977.
- [12] Yueh S. and J. Chaubell, "Sea Surface Salinity and Wind Retrieval using Combined Passive and Active L-Band Microwave Observations", *IEEE Trans. Geosci. Remote Sens.*, Vol. 50, No. 4, pp. 1022-1032, April 2012.
- [13] Yueh, S. H., W. Tang, A. Fore, G. Neumann, A. Hayashi, A. Freedman, J. Chaubell, and G. Lagerloef, "L-band Passive and Active Microwave Geophysical Model Functions of Ocean

- Surface Winds and Applications to Aquarius Retrieval,” *IEEE Trans. Geoscience and Remote Sensing*, 51(9), 4619-4632, DOI: 10.1109/TGRS.2013.2266915, 2013.
- [14] Burton, S. Garbow, Kenneth E. Hillstrom, Jorge J. More, Documentation for Minpack, Argonne National Laboratory, <http://www.netlib.org/minpack/>
  - [15] Figa-Saldaña, J., J.J.W. Wilson, E. Attema, R. Gelsthorpe, M.R. Drinkwater, and A. Stoffelen, The advanced scatterometer (ASCAT) on the meteorological operational (MetOp) platform: A follow on for European wind scatterometers, *Can. J. Remote Sensing*, Vol. 28, No. 3, pp. 404–412, 2002.
  - [16] Tang, W., S. Yueh, A. Fore, G. Neumann, A. Hayashi, and G. Lagerloef, “The rain effect on Aquarius’ L-band sea surface brightness temperature and radar backscatter”. *Remote Sensing of Environment*, 137, 147-157, 2013.
  - [17] Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., & Schlax, M. G. , “Daily high-resolution blended analyses for sea surface temperature”. *J. Climate*, 20, 5473-5496, 2007.
  - [18] Chassignet, E. P., H.E. Hurlburt, E. J. Metzger, O. M. Smedstad, J. Cummings, G. R. Halliwell, R. Bleck, R. Baraille, A. J. Wallcraft, C. Lozano, H. L. Tolman, A. Srinivasan, A. Hankin, P. Cornillon, R. Weisberg, A. Barth, R. He, F. Werner, & J. Wilkin, “U.S. GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model (HYCOM)”. *Oceanography*, 22(2), 64-75, 2009.
  - [19] Fore, A. G., S. H. Yueh, W. Tang, and A. K. Hayashi, “Aquarius Wind Speed Products: Algorithms and Validation”, *IEEE Trans. Remote Sens.*, Vol. PP, No.99, pp.1,8, 0. doi: 10.1109/TGRS.2013.2267616.
  - [20] Yueh, S., W. Tang, A. Fore, A. Hayashi and Y. T. Song, “Aquarius Geophysical Model Function and Combined Active Passive Algorithm for Ocean Surface Salinity and Wind Retrieval”. *J. Geophys. Res.-Oceans*, DOI: 10.1002/2014JC009939, 2014.
  - [21] Tang, W., S. H. Yueh, A. Fore, A. Hayashi, T. Lee, and G. Lagerloef, “Uncertainty of Aquarius sea surface salinity retrieved under rainy conditions and its implication on the water cycle study”. *J. Geophys. Res.-Oceans*, DOI: 10.1002/2014JC009834, 2014.
  - [22] Tang, W., S. H. Yueh, A. Fore, and A. Hayashi, “Validation of Aquarius sea surface salinity with in situ measurements from Argo floats and moored buoys”. *J. Geophys. Res.-Oceans*, DOI: 10.1002/2014JC010101, 2014.
  - [23] Yueh, S. H., W. Tang, A. G. Fore, and A. Hayashi, “Impact of Ocean Wave Height on L-band Passive and Active Microwave Observation of Sea Surfaces. The Special Issue of the IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS) “Aquarius/SACD mission calibration/validation performance and retrieval algorithms”, (accepted) 2015.
  - [24] W. E. Asher, A. T. Jessup, R. Branch, and D. Clark, “Observations of rain-induced near-surface salinity anomalies”, *J. Geophys. Res. Oceans*, 119, doi: 10.1002/2014JC009954, 2014.
  - [25] A. Santos-Garcia, M. M. Jacob, W. L. Jones, W. E. Asher, Y. Hejazin, H. Ebrahimi, and M. Rabolli, “Investigation of rain effects on Aquarius sea surface salinity measurements”, *J. Geophys. Res. Oceans*, 119, 7605–7624, doi:10.1002/2014JC010137, 2014.
  - [26] Tang, W., S. H. Yueh, A. Hayashi, A. G. Fore, W. L. Jones, A. Santos-Garcia, and M. M. Jacob, “Rain-induced near surface salinity stratification and rain roughness correction for Aquarius SSS retrieval”. Submitted to The Special Issue of the IEEE Journal of Selected

Topics in Applied Earth Observations and Remote Sensing (JSTARS) “Aquarius/SACD mission calibration/validation performance and retrieval algorithms”, 8 (12), 5474-5484, DOI: 10.1109/JSTARS.2015.2463768, 2015.

- [27] R. J. Joyce, J. E. Janowiak, P. A. Arkin, and P. Xie, “Cmorph: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution”, *Journal of Hydrometeorology*, 5, 487-503, doi:10.1175/1525-7541, 2004.
- [28] P. Xie, R. Joyce, S. Wu, and F. Sun, “Reprocessed and bias-corrected CMORPH global high-resolution precipitation estimates for weather, climate, and hydrometeorological applications”. 7th International Precip Working Group (IPWG) Workshop, Nov. 17-20, 2014, Tsukuba, JAPAN, 2014.
- [29] Roemmich, D., and the Argo Steering Team, “Argo: The challenge of continuing 10 years of progress”, *Oceanography*, 22, 46–55, 2009.
- [30] McPhaden, M. J., The TAO array is completed. *Bull. Amer. Meteor. Soc.*, 76, 739–741, 1995.
- [31] McPhaden and Coauthors (2009), RAMA: The Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction. *Bull. Amer. Meteor. Soc.*, 90, 459–480, 2009.
- [32] Servain, J., A. Busalacchi, M. McPhaden, A. Moura, G. Reverdin, M. Vienna, and S. Zebiak: “A Pilot Research Moored Array in the Tropical Atlantic (PIRATA)”. *Bull. Amer. Meteor. Soc.*, 79, 2019–2031, 1998.